Physics Advisory Committee

June 18-23, 2005

Comments and Recommendations

FERMILAB'S FUTURE PLANS

Fermilab's current program in particle physics is being carried out at a time of great excitement and promise. The Tevatron is operating very well, delivering a steadily increasing luminosity characterized by a data-doubling time that is now one year and is expected to remain below two and a half years throughout the decade. The CDF and DZero experiments are producing a rapidly growing stream of new results based on Run II data. The discovery of neutrino oscillations is the first observation of physics beyond the Standard Model and has inspired new experiments aimed at exploring the nature of neutrino-flavor physics. The Laboratory's Booster and Main Injector facilities are functioning extremely well and are both now providing high-intensity proton beams for neutrino production. Data-taking for the MiniBooNE experiment is well advanced and the community eagerly awaits its results. The MINOS experiment has brought its construction phase to a successful conclusion and has begun to acquire data. Fermilab is also playing an essential role in the construction of the LHC accelerator and the CMS detector and is well along in establishing itself as a center for CMS physics analysis. Finally, the Laboratory is conducting a small, but well-motivated and successful, research program in astroparticle physics.

The Laboratory staff and their domestic and international collaborators can be justifiably proud of these accomplishments, which were made possible by years of sustained investment. The Committee commends the Laboratory on so effectively carrying out its mission as the central facility for particle physics in the U.S.

There are, however, dangers to the U.S. program. With no new investment, the number of high-energy physics opportunities in the U.S. will dwindle as we approach the end of the decade. This state of affairs threatens the vitality of the field just at a moment of great opportunity, when profound scientific mysteries still remain unresolved. Furthermore, the fiscal situation is such that this dilemma will not be easily remedied. Careful planning is essential, and difficult decisions will need to be taken.

The Laboratory presented a well considered plan that addresses these challenges and offers a path to keep the U.S. in a position of leadership. In particular, it proposes to carry through with Run II at the Tevatron, thus taking advantage of what will be unique opportunities to exploit the discovery potential at the energy frontier and to elucidate the important question of electroweak symmetry breaking. Taken together with the Laboratory's involvement in CMS, this plan will provide continuity in the collider physics program. Fermilab also proposes to build on its investment in NuMI/MINOS by constructing the NOνA experiment as the next logical step in a program to explore the neutrino-flavor puzzle.

Fermilab's plans also call for a significant ramp-up in International Linear Collider (ILC) R&D, aimed at hosting this important endeavor, and providing vital infrastructure whether or not the ILC is eventually built near Fermilab. The plan maintains an alternative path in the form of a Proton Driver that would be built in the event that the ILC is delayed or does not go forward. The overlap between ILC and Proton Driver technology allows the latter to be pursued in a way that will not materially detract from work on the ILC, but rather will offer synergistic advantages.

The Committee enthusiastically endorses the basic features of this plan, while recognizing that its successful implementation will require a highly disciplined approach. Indeed, even with such discipline, full realization of the Laboratory's core plans may not be possible without a temporary increase in funding toward the end of the decade.

NEUTRINO PHYSICS AND THE PROTON DRIVER

The Context

The discovery of neutrino mass and mixing has led to a number of very interesting questions: What are the (presently rather uncertain) neutrino mass splittings, Δm^2? Is the surprisingly large atmospheric mixing angle maximal? If so, is an underlying symmetry responsible? Is the neutrino mass spectrum normal, as favored by grand unified theories, or inverted? Do neutrino interactions violate CP symmetry, and if they do, is this violation related to the observed matter – antimatter asymmetry of the universe? How small is the presently unknown mixing angle θ_{13}, on which CP violation in neutrino interactions and our ability to determine whether the mass spectrum is normal or inverted both depend? To answer these questions, the APS multi-divisional neutrino study recommended that high priority be given to a timely accelerator neutrino experiment, and then to a Proton Driver in the megawatt class with more sensitive experiments. The Committee believes that the case for the recommended program is very strong. Timeliness is indeed important because of the complementary accelerator neutrino program being mounted in Japan and because of the probable timing of complementary, and related, reactor neutrino experiments. Fermilab has an active ongoing neutrino program relevant to these issues, and is well-poised to play a major role in future research in this area.

NOνA

NOνA presented updates on physics sensitivity studies, detector design technical progress, and project management issues, including answers to several questions raised by the PAC before the Aspen meeting.

Physics Sensitivity and Experimental Strategy

NOνA is considering a 5-year run strategy with a mixture of neutrino and anti-neutrino running. This strategy gives a 95% C.L. sensitivity on $\sin^2 2\theta_{13}$ of ~0.01, with relatively small dependence on the CP phase δ, for a total of 32×10^{20} protons on target. This reach is similar to that of the most sensitive proposed reactor experiments.

In addition to sensitivity to the angle θ_{13}, the approved NOνA experiment has modest but unique sensitivity to the mass hierarchy. Moreover, with a Proton Driver (PD) capable of delivering approximately a factor of four higher proton intensity, combined with a second detector at 30 km off-axis, the neutrino program can determine the mass hierarchy for any $\sin^2 2\theta_{13}$ greater than ~0.02. The upgraded configuration is also capable of a 3σ observation of CP violation for more than 50% of the CP phase space if $\sin^2 2\theta_{13}$ is >0.02. These exciting prospects would address fundamental physics questions in the neutrino sector.

Matter effects (which depend on the hierarchy) and CP violation both produce an asymmetry between neutrino and antineutrino oscillation probabilities. However, because the Fermilab neutrino beamline is longer and of higher mean energy than its J-PARC counterpart, the contribution of matter effects to the neutrino – antineutrino asymmetry will be larger at Fermilab than at J-PARC. Thus, combining the results of measurements with upgraded facilities at the two places will significantly enhance the ability to separate genuine CP violation from matter-induced asymmetries.

NOνA presented several studies related to optimization of the experimental design. One of these studies indicates that a detailed optimization of the beam energy profile could improve statistics by ~10%. An updated study on cosmic ray background was presented. The cosmic muon and neutron backgrounds are easily distinguishable from ν_e signal events. The electron and photon backgrounds are not as easy to control, which led to a design preference to include an overburden of ~3m of rock. This adds ~11M$ of cost, but has the benefit of making it possible to use NOνA as a supernova detector with much better signal/background. The Committee notes the following remaining unanswered issues: a) extent to which MIPP/MINERνA can help estimate far-detector backgrounds by extrapolating from the near detector; b) energy reconstruction accuracy as a function of neutrino energy, down to the lowest relevant energy. The proposed mixture of running with neutrinos and antineutrinos also demands studies of backgrounds, which will be different for neutrinos and antineutrinos. The Committee hopes that NOνA will provide information regarding these issues to the Laboratory in time for the next PAC meeting.

Technical Progress

The collaboration has made good progress towards a final design for the extruded PVC tanks for the liquid scintillator. They have developed a new scalloped cell design with a larger radius of curvature (3/8") at the corners to reduce the stress by about a factor of two. They are planning to study short prototype cells, pressurizing them to simulate the additional pressure head associated with the tall structures to be employed in the full detector. The Committee encourages the collaboration to continue these technical studies and to address the various other detector design issues. Tests to ensure that there are no stress-related chemical effects due to the presence of liquid scintillator should also be undertaken.

The photoelectron (Pe) yield of a prototype liquid scintillator cell with wave-length shifting fiber attached to avalanche photodiode (APD) readout was measured. The design goal is 25 Pe per minimum ionizing particle at the end far from the APD, and the observed yield was 24 Pe. Further improvements in reflectivity of the PVC cell walls are anticipated to increase the yield further. However, the width of the observed distribution was significantly wider than expected from a 24 Pe yield. This width was apparently not well understood at the time of this meeting and is under further study.

Alternate Site

The collaboration is now considering an alternate site for the experiment. This alternate site may have more convenient road access and power availability. Feasibility studies and a choice of site should be accomplished in a timely fashion. If the alternate site is still under consideration at the next PAC meeting, the Committee would like to see its effects on the experimental sensitivity.

NOνA Summary

The Committee would like to reiterate the importance of timeliness in the implementation of NOνA. There is substantial value in starting the experiment as soon as possible to maintain a competitive position in discovering ν_e appearance and measuring θ_{13}. Reactor experiments, as well as T2K, are aiming to address the θ_{13} issue early in the coming decade. An initially quite modest beam power at T2K in 2009 will be gradually ramped up until 2013. Given the remaining work to be done and the extensive review process that lies ahead, it will be a great challenge to construct NOνA and begin taking data on a competitive time scale; nevertheless, it does appear possible at this point if substantial delays can be avoided. Timely execution of this important experiment will require serious attention from both the collaboration and Laboratory management.

In addition to the potential for discovering the important mixing parameter θ_{13}, NOνA will provide opportunities for studying both the mass hierarchy <u>and</u> CP violation in the neutrino mixing matrix. Indeed, the long baseline afforded by the NOνA experiment makes it uniquely sensitive to the mass hierarchy. Thus a large share of the future of neutrino physics will be accessible at Fermilab with the existence of NOνA and subsequently with suitable upgrades (e.g., Proton Driver and additional detector deployments). This program will provide the Laboratory with a unique and world-leading role in the exciting field of neutrino physics for many years to come, with substantial opportunities for important discoveries.

<u>Proton Driver</u>

The currently favored scheme for a Proton Driver at Fermilab (FPD) is based on a new 8 GeV superconducting linac. Feeding the Main Injector, this linac could produce a beam with an initial, upgradeable power of 2 MW at any energy from 40 to 120 GeV. This linac could simultaneously provide an 8 GeV beam with an initial power of 0.5 MW, upgradeable to 2 MW.

The Committee heard a progress report on Proton Driver R&D from the Technical Division. The proposal is to build an 8 GeV Proton Driver using Tesla technology, with the $\beta < 1$ sections using "squeezed" Tesla cavities and the $\beta \sim 1$ sections using cavities very similar to those proposed for the ILC. Possible locations for such a facility on the Fermilab site have been evaluated.

The Proton Driver project has substantial overlap with ILC development and industrialization. The $\beta=1$ section of the Proton Driver will consist of 36 ILC cryomodules, equivalent to 1.5% of a 500 GeV ILC. Due to the large overlap in accelerator technology, Proton Driver development is closely tied to ILC R&D, and Fermilab is pursuing a strategy that emphasizes the ILC but also advances the Proton Driver. It is believed that the number of klystrons needed per GeV of acceleration can be reduced substantially relative to the number used at SNS by the use of phase shifters to independently control the phase and amplitude of the RF in each individual cavity. This technology still needs to be tested with beam but is vital to a low cost machine. Additional goals for the next two years are to establish a capability to fabricate and test high-gradient cavities and a facility for high-power tests of integrated cryomodules. The venue for this work will be the SMTF (Superconducting Module Test Facility). This R&D is essential for both the ILC and the proposed Proton Driver.

The physics case for a Fermilab Proton Driver, presented to the Committee by Stephen Geer, is compelling. To establish that neutrino interactions violate CP and to greatly improve sensitivity to the hierarchy question will require event rates substantially higher than will be available with NOνA at NuMI. The FPD would provide such higher event rates and thus play a key role in the exploration of neutrino mass, mixing, and CP violation. This role is the primary reason, and a convincing reason, for building the FPD. Although the neutrino event rates could also be raised by increasing detector mass, that approach offers no clear cost advantage. In addition, it would lack the versatility provided by an FPD, which could also produce variable energy neutrino and other beams as needed. The 8 GeV FPD proton beam would make possible precision studies of muons, while the higher-energy beam would make possible studies of rare kaon decays. Whether or not the LHC observes new physics beyond the Standard Model, studies such as these can provide important information about the existence and nature of new physics at higher mass scales. These studies will be particularly interesting if the LHC does see new physics, because they will be needed to help elucidate the characteristics of the new phenomena. Finally, it is important to note that an FPD would be a logical first step towards the development and implementation of a neutrino factory, which could provide a powerful new world-class capability in neutrino physics in the future.

The Paths Into The Future

As discussed above, a Fermilab Proton Driver would bring great benefits, including:

- The ability to establish the presence of CP violation in neutrino oscillations, and to determine the neutrino mass hierarchy, for any value of θ_{13} almost down to the 95% C.L. sensitivity on $\sin^2 2\theta_{13}$ (~ 0.01) achievable with conventional neutrino beams.

- Neutrino beams at several energies, enabling antineutrino cross section measurements at the low energies where they are needed.

- A window on new physics beyond the Standard Model via muon and kaon studies.

- An ILC technology developmental tool.

- A first component of a neutrino factory.

- Improved reliability of the accelerator complex.

However, if a decision is made to build an ILC without delay at Fermilab, then construction of the Fermilab Proton Driver is unlikely. In that case, one can still create more intense neutrino beams by upgrading the existing accelerator complex in steps. Each step involves uncertainties, which compound as one takes more steps. However, it appears likely that a proton beam power of at least 1 MW, corresponding to 10^{21} protons on target/yr at 120 GeV, can be achieved. This flux would provide NOνA with considerable physics reach, even without the FPD. Unfortunately, the benefits of a Fermilab Proton Driver discussed above would be lost in such a scenario.

This vision of possible neutrino physics futures at Fermilab, which has been presented by the incoming Fermilab Director, is one with which the Committee strongly concurs.

Summary

The Committee recommends continuing R&D on the very attractive Proton Driver possibility and investigation of the non-Proton-Driver upgrades to the proton beam intensity. The Committee notes that some of these latter upgrades, notably those involving modifications to the Main Injector, would also increase the beam intensity provided with a Proton Driver.

Even without the Proton Driver, a neutrino program with considerable reach and importance to the world's exploration of neutrino physics can be carried out. With the Proton Driver, the Fermilab neutrino program can determine the mass hierarchy and establish CP violation so long as $\sin^2 2\theta_{13} > (0.01\text{-}0.02)$. Should θ_{13} prove to be below this level, the Proton Driver can serve as a component of the neutrino factory that would then be required for future studies. As we have discussed, a Proton Driver will also yield many additional scientific, operational, and technical benefits.